1 eRHIC Project Overview

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1.1 Design Considerations and Design Options

1.1.1 Main Design Considerations

The electron-ion collider (EIC) has been recognized as the next high priority large experimental facility in the 2015 DOE Nuclear Physics Long Range Plan [1]. Brookhaven National Laboratory suggests a cost effective path to the EIC by taking advantage of the existing RHIC heavy ion collider facility. Inside the present RHIC tunnel an electron accelerator will be added to deliver polarized electron beam for collisions with RHIC polarized protons or heavy ions. This new electron-ion collider based on the existing RHIC facility is named as eRHIC.

The EIC physics case was outlined in the EIC White paper [2] as well as in the 2014 eRHIC Design study paper [3]. It aims to explore with unprecedented detail the structure of the nucleon and the nucleus, and answer outstanding questions on the role that gluons play in the QCD processes defining the nucleon/nucleus structure. The eRHIC accelerator design has been developed to fulfill the EIC physics case goals. It entails the following major features:

- Hadron species: polarized protons (up to 250 GeV), polarized $^{3}He^{+2}$ ions (up to 167 GeV/u), heavy ions (typically $^{197}Au^{+79}$ or $^{238}U^{+92}$ ions, up to 100 GeV/u).
- Polarized electrons: up to 20 GeV.
- A wide Center-of-Mass energy range covering from 20 to 140 GeV.
- High polarization (70% or more) of protons, $^{3}He^{+2}$ ions and electrons at all energies. Bunch spin pattern, consisting of electron and proton bunches with opposite polarization.
- The luminosity in the 10^{32} - 10^{34} $cm^{-2}s^{-1}$ range.
- Full acceptance detector, including IR-integrated detector components for forward collision products detection. A place for second detector is reserved.

The first electron-proton collider HERA operated in 1990-2007 in DESY Laboratory (Germany), achieving in its final operation years, after realizing the luminosity upgrade, a peak luminosity of $5 \cdot 10^{31}$ $cm^{-2}s^{-1}$. It employed the ring-ring collision scheme, where protons as well as polarized electrons circulated in individual storage rings. HERA did not accelerate any ion beam other than unpolarized protons. eRHIC must well exceed the HERA luminosity achievement. Besides that, a polarization level for electron and proton beams, exceeding 70 % is required. And, unlike HERA, eRHIC will provide the capability of electron collision with a heavy ion beam.

The quest for a high luminosity collider calls for advanced accelerator technologies able to achieve this goal. The key goal of the eRHIC accelerator design has been to achieve the required high-energy, high-luminosity performance at a reasonable level of risk related with using advanced technologies and at a realizable machine construction cost .

The present luminosity-staged design approach to eRHIC, described in this report, balances the costs and risks and is based on the following considerations:

- The configuration of any design option of eRHIC should have enough center-of-mass reach (20 GeV pol. e x 250 GeV pol. p and 20 GeV e x 100 GeV/n Au) and detector acceptance to cover the whole EIC science case.
- The luminosity at an initial stage could be lower and then increased through incremental upgrades, as was done for RHIC and other colliders.

Figure 1-1 presents the staging scenario using three design options, overlapped with the areas of eRHIC physics program. It includes lower luminosity design options, called Nominal designs, based on Linac-Ring (LR) and Ring-Ring (RR) design approaches. Any of these Nominal designs can later be upgraded to a high luminosity Ultimate eRHIC design, which is based on the Linac-Ring approach.

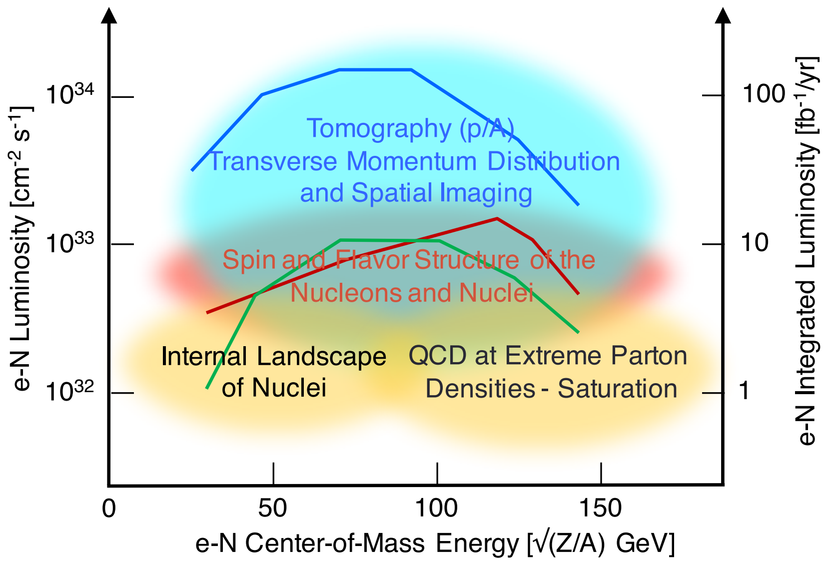

Figure 1-1: eRHIC peak luminosity versus CoM energy for three design options considered in this report. Green curve: Nominal Linac-Ring design. Red curve: Nominal Ring-Ring design. Blue curve: Ultimate design.

1.1.2 Nominal and Ultimate Linac-Ring Design Options

The Linac-Ring design approach employs electrons accelerated in a re-circulating energy recovery linac (ERL), which then collide with the ion beam just once (or twice, if a second detector is used). Such an approach removes the limitation of the beam-beam effect of the high-energy hadron beam on the lower energy electron beam. It opens a path to very high luminosity by using a small transverse beam cross-section at the collision point.

Hadron cooling is required to shrink transverse and longitudinal beam emittances, with stronger cooling leading to higher achievable luminosities. The cooling also helps to satisfy detector requirement for small forward angular divergence. The Ultimate LR design uses very strong cooling that reduces the transverse emittance by a factor 10 leading to a luminosity above 10^{34} s^{-1} cm^{-2}. Such strong cooling can be realized by applying a novel cooling technique, Coherent electron Cooling (CeC). The development of CeC technology is a very important subject of the eRHIC R&D program.

At collision point the required electron beam current in the LR design approach is an order of magnitude less than that of RR design. This design approach results in considerably lower synchrotron radiation (SR) produced by the beam in the transport beamlines. A SR power limit of 2.5 MW has been accepted for the LR design. Nevertheless, there is a significant technological challenge since this electron current has to be generated by a polarized electron source. The Ultimate LR design requires an electron current of 50 mA to reach 10^{34} s^{-1} cm^{-2} luminosity, which is well beyond the present state-of-the-art. R&D for high-current polarized electron source is crucial for the LR design approach.

To increase the luminosity level at lower proton energies the Ultimate design incorporates space charge compensators. They arrange an interaction of circulating hadron beam with low energy electron beam in order to reduce the space-charge tune spread.

The Nominal LR design option aims at a luminosity level of 10^{32}-10^{33} s^{-1} cm^{-2}. Reaching this luminosity level requires considerably weaker hadron cooling as well as smaller polarized electron current than in the Ultimate design option. Thus, the Nominal LR design has reduced technological risks as compared with the Ultimate design. To provide the weaker cooling classical electron cooling technology is being considered, although applying classical electron cooling for protons at energies as high as 250 GeV still presents a considerable challenge.

In the Linac-Ring design options the electron beam acceleration is done by multiple re-circulations through an energy recovery linac. This ERL is located in a long straight section of the RHIC tunnel and based on 650 MHz SRF cavities. SRF cavities of this frequency have been successfully developed at Fermilab. Multiple re-circulations of the electron beam are realized by only two transport beamlines based on a linear Fixed-Field Alternating Gradient (FFAG) lattice. FFAG-lattice beamlines are capable of transporting beams in a wide energy range at the same time and can be built with permanent magnets. An additional individual transport beamline is needed to bring the high energy electron beam to the collision areas. Using technologies like the ERL, permanent magnet arcs and strong cooling of hadron beam greatly reduces electric power consumption, thus minimizing the operation cost and conserving resources.

Chapter 2 presents the accelerator design of the LR design options.

1.1.3 Nominal Ring-Ring Design Option

In the Ring-Ring design approach the high intensity electron beam is stored in a circular storage ring. 10^{32}-10^{33} s^{-1} cm^{-2} luminosity covering whole energy range of EIC science case is possible. It requires little or no hadron cooling to operate at this luminosity level. Compared with HERA, the circulating electron current can be much larger because of the lower electron energy. The accelerator technologies required to provide the storage of high-intensity electron beam are at the level of successful high luminosity electron-positron colliders of recent past, B-factories. The electron current is limited by synchrotron radiation power. The compensation of SR power loss is a considerable cost driver and 10 MW SR power limit is currently assumed.

The RR design calls for increased bunch repetition rate, by a factor 3 from present RHIC, envisioning an upgrade of the RHIC injection system.

The electron storage ring needs to operate over a wide energy range, maintain electron polarization by containing depolarizing effects, and include spin rotators. Spin experiments need bunch-to-bunch spin sign control. For the Ring-Ring design option this requires full energy injector and frequent electron bunch replacement. To accomplish it a CEBAF-like accelerator (same as the ERL but no energy recovery) in the RHIC tunnel can be used.

The storage ring is very similar to the final pass in the LR design options. An upgrade to the higher luminosity Ultimate LR design is possible by recovering the electron beam energy in the CEBAF-like injector, converting it into an ERL. Thus, the injector design is identical to the design of the re-circulating SRF linac of the LR design options. Particularly, the same SRF cavities have to be used and the electron re-circulations must be based on the FFAG lattice to make the future upgrade to the Linac—Ring Ultimate design cost effective.

The Nominal RR design option is described in Chapter 3.

1.1.4 Hadron Ring Modifications

The present RHIC accelerator uses superconducting magnets to circulate hadron beams in two rings of 3834 m circumference. The wide energy reach of RHIC provides a natural opportunity to operate eRHIC over a wide range of center-of-mass collision energies. Existing proven accelerator technologies, exploited in RHIC and its injectors to produce and preserve proton beam polarization, will provide the highly polarized proton beam required for the eRHIC experiments.

At the eRHIC era no continuing RHIC operation as proton or heavy ion collider is planned. Hence, various modifications of the present RHIC machine for eRHIC design purposes can be considered, assuming moderate cost of such modifications. Among the biggest hadron ring modifications are:

- new interaction region magnets to satisfy eRHIC interaction region requirements
- additional Siberian Snakes required for acceleration of polarized $^3He^{+2}$
- a hadron cooling device in the IR10 area
- copper coating of the beam pipe to reduce pipe wall heating and related cryogenic load

Besides specific eRHIC design options may have additional required modifications described in corresponding Chapters of this report.

1.2 Main Beam Parameters

The design luminosity and choice of beam parameters are influenced by physical limits as well as practical considerations. Some of the limiting factors, such as maximum values of the hadron beam-beam and space-charge parameters, come from operational and experimental observations at RHIC and other hadron colliders. Others, like polarized electron source current, are defined by anticipated limits of accelerator technology. Other important limits for eRHIC beam parameters are defined by detector requirements (the beam angular spread at IP) and by cost considerations (synchrotron radiation power loss).

The major common limits assumed for the beam parameters in all design options are:

- Hadron beam-beam parameter: $\xi_h \leq 0.015$
- Proton beam angular spread at the IP (at 250 GeV): 120 murad or less (at least in one plane)
- Hadron space-charge tune shift: $\Delta Q_{sp} \leq 0.06$ (with space charge compensation in the LR Ultimate design)

The LR design options has specific limiting factors:

- Polarized electron current: 26 mA (Nominal design), 50 mA (Ultimate design)
- Electron synchrotron radiation power: $P_{SR} < 2.5$ MW

Specific parameter limits for RR design option are:

- Electron beam-beam parameter: $\xi_e \leq 0.1$
- Electron synchrotron radiation power: $P_{SR} < 10$ MW

The main beam parameters and luminosities of the highest luminosity modes of all three eRHIC design options are listed in Table 1-1 (for e-p) and Table 1-2 (for e-Au). The luminosity calculation includes factors related to the hourglass effect and, for LR options, to the IP electron pinching. The high luminosity of RR Nominal design is achieved mainly due to high electron and proton currents, circulated in storage rings. On the other hand, the high luminosity of LR designs is mostly due to small beam sizes at the interaction point, which is achieved, in part, by transverse hadron beam cooling.

Table 1-1: Beam parameters for highest luminosity of e-p collisions for the three design options.

	RR Nominal design		LR Nominal design		LR Ultimate design	
	e	p	e	p	e	p
Energy [GeV]	13.7	250	10	250	8.3	250
CM energy [GeV]	117		100		91	
Bunch frequency [MHz]	28.2		9.4		9.4	
Bunch intensity [10^{10}]	21	22	1.7	20	3.3	30
Beam current [mA]	935	990	26	277	50	415
rms norm.emittance h/v[um]	1430/250	2.5/2.5	36.7/36.7	0.5/0.5	16.5/16.5	0.27/0.27
rms emittance h/v [nm]	53/9.4	9.4/9.4	1.9/1.9	1.9/1.9	1.0/1.0	1.0/1.0
beta*, h/v [cm]	38/27	216/27	12.5/12.5	12.5/12.5	7/7	7/7
IP rms beam size h/v [um]	142/50		15.3/15.3		8.4/8.4	
IP rms ang. .spread h/v [urad]	375/186	66/186	120/120	120/120	120/120	120/120
max beam-beam parameter	0.1	0.015	1.2	0.004	4.1	0.015
e-beam disruption parameter			20		36	
max space charge parameter	4e-5	0.001	1.4e-4	0.006	8.6e-4	0.058
rms bunch length [cm]	1	20	0.3	16.5	0.3	5
Polarization [%]	80	70	80	70	80	70
Peak luminosity [$10^{33}cm^{-2}s^{-1}$]	1.4		1.0		14.4	

Table 1-2: Beam parameters for highest luminosity of e-Au collisions for the three design options.

	RR Nominal design		LR Nominal design		LR Ultimate design	
	e	Au	e	Au	e	Au
Energy [GeV/u]	13.7	100	10	100	8.3	100
CM energy [GeV]	74		63		58	
Bunch frequency [MHz]	28.2		9.4		9.4	
Bunch intensity [10^{10}]	21	0.2	1.7	0.2	3.3	0.2
Beam current [mA]	935	710	26	219	50	219
rms norm.emittance h/v[um]	1420/	1.0/1.0	29/29	0.16/0.16	24/24	0.16/0.16
rms emittance h/v [nm]	53/9.4	9.4/9.4	1.5/1.5	1.5/1.5	1.5/1.5	1.5/1.5
beta*, h/v [cm]	38/27	216/27	12.5/12.5	12.5/12.5	7/7	7/7
IP rms beam size h/v [um]	142/50		13.6/13.6		10.2/10.2	
IP rms ang. .spread h/v [urad]	375/186	66/186	109/109	109/109	146/146	146/146
max beam-beam parameter	0.073	0.015	1.2	0.0053	1.5	0.01
e-beam disruption parameter			20		29	
max space charge parameter	4e-5	0.005	1.5e-4	0.039	6e-4	0.058
rms bunch length [cm]	1	20	0.3	16.5	0.3	11
Polarization [%]	80	0	80	0	80	0
Peak luminosity [$10^{33}cm^{-2}s^{-1}$]	2.5		2.5		8.0	

1.3 The R&D Program

1.3.1 Introduction to the eRHIC R&D Program

The R&D Program comprises two parts: The Pre-Project and the On-Project R&D. The key goal of the eRHIC accelerator Pre-Project R&D program is risk reduction for the eRHIC Project. The aim of the On-Project R&D program is prototyping and value engineering.

The Pre-Project R&D Program aims at the various elements of the Linac-Ring eRHIC. This includes numerical simulation and theory of the multiple aspects of the eRHIC Linac-Ring design, the results of which are included in other sections of this document. However the items considered as high-risk include experimental programs: R&D on highly-damped Superconducting RF (SRF) accelerating cavities; R&D of SRF crab cavities and testing the performance of crab cavities in a high-energy hadron machine; R&D of high-current polarized electron gun; R&D of FFAG multi-pass ERL; R&D of strong hadron cooling, in particular magnetized electron cooling for the Nominal design and Coherent electron Cooling for the Ultimate design of eRHIC.

The full extent of the On-Project R&D Program is yet to be determined, but we anticipate the following major elements:

Prototyping of a complete girder of eRHIC FFAG magnets, correction magnets, vacuum, beam instrumentation, power and control; Prototyping all major SRF cavities and their fully dressed cryomodules and high-level RF and low-level RF, including the ERL cavities, the crab cavities and the low-frequency injection and cooler linac acceleration cavities; Prototyping the polarized electron gun; Prototyping a superconducting solenoid section of the magnetized electron cooler.

Value engineering of performance enhancements of SRF cavities such as nitrogen doping and/or niobium-three-tin coating; Value engineering of fast, high-power reactive tuning of SRF cavities; Value engineering of cryomodules and their components such as tuners, alignment methods; Value engineering of beam instrumentation; Value engineering of high-efficiency RF amplifiers.

The On-Project R&D program will be formulated in greater detail before CD0.

1.3.2 The Pre-Project eRHIC R&D Program

The Pre-Project R&D Program has been going on for a while side-by-side with the evolution of the eRHIC design. The program has been guided by various advisory committees as well as ad-hoc reviews. The Electron Ion Collider Advisory Committee was established as a joint initiative of BNL and JLab laboratories directors, to periodically review EIC progress and to provide feedback on the project development, including the prioritization of the accelerator R&D program. The C-AD standing Machine Advisory Committee provides guidance to the various C-AD accelerator issues including the eRHIC R&D. A Director's Review Committee of eRHIC R&D has been established in 2015 to closely guide the C-AD eRHIC R&D program. In addition to these regular committees the eRHIC Pre-Project R&D program has been guided by frequent ad-hoc reviews/advisory committees such as on eRHIC design, R&D ERL, Coherent electron Cooling and Polarized Gun.

R&D on highly-damped superconducting RF (SRF) accelerating cavities

The eRHIC high current SRF ERL generates a large HOM power and requires good HOM damping. Good damping is also essential to increase the beam current threshold of the multi-pass, multi-bunch beam breakup instability (BBU) This HOM damping issue was recognized as a high-risk item early on in the eRHIC program [4] in particular since the HOM power generated in eRHIC cavities is unprecedented. The first 5-cell SRF cavity selected for eRHIC service was designed built and tested using BNL Program Development funding. This cavity, at a frequency of 703.75 MHz and designated as “BNL-1”, was the first strongly HOM damped multi-cell SRF cavity. HOM damping was obtained by beam-pipe ferrite absorbers [5]. It performed well in vertical tests up to 20 MV/m, but was limited to pulsed operation above 10 MV/m in horizontal testing due to a faulty beam-line gasket.

The second cavity to be built and tested was the BNL-3 cavity [6]. This cavity was funded by DOE HEP grant aimed at the CERN SPL linac. This was also a 5-cell 703.75 MHz SRF cavity with all HOM modes well damped, but further optimization of the damping, peak surface electric and magnetic fields, loss factor, shunt impedance and geometrical factor was done. The main design difference from the BNL-1 cavity was to include ports for six coaxial HOM dampers located on the beam pipes. Two cavities have been built and tested vertically, and one of them is now installed in the CeC PoP experiment [7].

The current experimental risk-reduction R&D on the eRHIC ERL main cavities is funded by two strategic LDRD grants, one for the design, construction and testing of a 650 MHz 5-cell SRF cavity, the other for development of strong HOM damping schemes to include damping of all HOM modes in the spectrum generated by the eRHIC beam, which extends to about 30 GHz and has a significant component above 5 GHz. This program is funded for the next three years and is aimed at mitigating the risk associated with HOM damping in the eRHIC ERL.

R&D of SRF crab cavities and testing the performance of crab cavities in a high-energy hadron machine

Crab cavity, also known as a deflecting cavity, is a resonator that is designed to apply a time dependent deflection to a particle beam crossing the cavity. Most applications of crab cavities require continuous operations at very high deflecting fields, thus they have to use RF superconductivity (SRF) technology. The high-risk element for eRHIC is due to the fact that crab cavities have not been ever used in hadron colliders.

There are various applications of deflecting cavities, such as in beam diagnostics, production of very short pulses and more. In the context of eRHIC and HL-LHC, the deflection is used to facilitate 'crab crossing', in which the two beams colliding in the interaction point (IP) do not collide head-on but with a small crossing angle. The reasons for using a crossing angle are mainly to reduce the long-range beam-beam interaction, and in the case of eRHIC to avoid bending the electron beam near the detector and thus significantly reduce the synchrotron radiation in the detector. However, the crossing angle also reduces the overlap of the colliding beams in the IP, thus introducing loss of luminosity that can be detrimental. Tilting the beams at the appropriate angle by the application of crab cavities restores the luminosity.

The idea and the name for crab crossing were introduced by BNL's Bob Palmer [8]. Crab crossing was applied to electron beams at the KEK B factory [9], but never to hadron beams. The first crab cavity workshop [10] took place at BNL. Since then there the R&D has been carried out through LARP funding to BNL. Initially crab cavities, as those used at KEK, were very large in size and complex and difficult in implementation. A search was mounted for compact and simple cavities. We designed a novel and suitably compact Double Quarter Wave Crab Cavity (DQWCC) [11] [12] that was constructed and successfully tested at BNL [13]. Crab crossing is a significant component of HL-LHC, and CERN is committed to large investments in the development of the subject. The DQWCC was recently adopted by CERN as the candidate for a critical test of crab cavities at the SPS. The program includes the construction of cavities, couplers, tuners, HOM dampers, the cryostat, and most importantly a test with beam at the SPS.

The success of this test will remove a major risk element from the eRHIC design at BNL.

R&D of high-current polarized electron gun

The luminosity of polarized beam linac-ring eRHIC is directly proportional to the current that can be produced by the polarized electron gun. The nominal eRHIC design requires 26 mA (2.8 nC bunches at a repetition frequency of 9.4 MHz), and the ultimate design calls for 50 mA. These requirements represent a high-risk element of the eRHIC design, thus motivating the R&D program to demonstrate high-current polarized electron beams. The current level of performance, spearheaded by JLab scientists reached about 4 mA from a relatively small cathode area (0.35 mm diameter Gaussian FWHM). The initial QE of the strained-superlattice GaAs/GaAsP photocathode was high: ~ 1.5%. This, combined with the maximum available laser power of 0.6W, allowed sustained operation at 4mA for approximately 1.4 hours. A total of 20C was extracted before exhausting QE and laser power headroom. An exponential fit to the QE decay indicates a charge lifetime of 85C.

One mechanism that is being explored to increase the current and charge lifetime is increasing the active cathode area. A significant mechanism limiting the operational lifetime of GaAs photoguns is ion back-bombardment, where residual gas in the cathode/anode gap is ionized by the exiting electron beam and then accelerated back toward the photocathode. These ions damage the GaAs crystal structure or sputter away the chemicals that are used to create the negative electron affinity (NEA) condition of the photocathode. For a larger laser spot size, the ion damage will be distributed over a broader area and consequently, it is expected that damage to specific photocathode locations will occur more slowly [14]. R&D towards this objective for eRHIC is being carried out in two approaches. The first is using a single large cathode [15], the other is by funneling multiple beams onto the axis of the accelerator from as many as 20 individual cathodes [16], [17]. The large single cathode may be appropriate for the nominal eRHIC parameters whereas the multiple cathode, or "Gatling Gun" approach may be necessary for the ultimate eRHIC performance.

R&D of FFAG multi-pass ERL

The eRHIC beam transport is based on two Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) rings [18]. While FFAG accelerators have been built and tested, including in particular the NS-FFAG electron accelerator EMMA [19], this transport lattice is considered a high risk for eRHIC on account of the large momentum range, energy recovery and high beam current. Therefore one of the largest experimental R&D efforts for eRHIC is the Cornell BNL FFAG-ERL Test Accelerator (CBETA, or Cβ) [20].

The Cβ will comprise the first ever electron Energy Recovery Linac (ERL) based on the Fixed Field Alternating Gradient (FFAG) lattice. The Cβ brings together the resources and expertise of a large DOE National Laboratory, BNL, and a leading research university, Cornell. The Cβ will be built at an existing building at Cornell University, using for the most part components that have been developed under previous R&D programs, including a fully commissioned world-leading photogun electron injector, a large SRF accelerator module and a high-power beam dump. The only element that requires design and construction from scratch is the FFAG magnet beam transport lattice.

The Cβ, operated in various modes, will allow tests high beam powers, high bunch charge, short bunch lengths, matching of arcs to FFAG, beam loss mechanism and control, multipass BBU theory, containment of beams with large energy spread, preservation of emittance, machine operation and tuning, diagnostics for FFAG's, ion trapping and more. It will present a prototype of eRHIC as complete as possible short of building eRHIC itself.

R&D of Coherent electron Cooling for the ultimate design of eRHIC.

The principle of Coherent electron Cooling (CeC) has been formulated by Derbenev [21] to amplify the collective response to an ion immersed in an electron plasma and use it to enhance the friction force of electron cooling. CeC combines principles of electron and stochastic cooling to dramatically increase the cooling rate. The amplification can take various forms, some of which were studied in detail, such as microwave instability amplification [22], FEL instability [23] and the micro-bunching instability [24]. The micro-bunching CeC promises significant increase in the bandwidth of the CeC system and, therefore, significant shortening of cooling time in high-energy hadron colliders. The CeC method has never been demonstrated, thus it presents a high risk factor for the ultimate eRHIC design. Therefore the CeC Proof-of-Principle (PoP) experiment has been proposed [25] and is funded mostly by EIC competitive R&D funding of the DOE Office of Nuclear Physics. The goal of this experiment is to demonstrate the cooling of the ion beam and to compare its measured performance with predictions made prior to the experiments. The experiment is installed in the RHIC ring and commissioning will start in January 2016. This experiment will allow the observation of longitudinal cooling of a single bunch of the RHIC beam using the FEL amplification technique. While a full demonstration of the micro-bunching instability cooling is very expensive to demonstrate in RHIC, key aspects of the mechanism will be possible to test in the CeC experimental system by the installation of a buncher magnetic system [26].

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